APPENDIX 3

REPORT OF ERIC N. BARNHART, P.E., CHIEF, COMMUNICATIONS & NETWORKING DIVISION GEORGIA INSTITUTE OF TECHNOLOGY

Analysis of Issues affecting LMDS Operation at 40 GHz

Introduction:

The purpose of this brief paper is to examine some of the issues affecting the potential operation of LMDS at 40 GHz instead of 28 GHz. For purposes of evaluation, it has been assumed that the principles of system operation are intended to be the same for the system at 40 GHz as they are at 28 GHz. Indeed, this is necessary to make the comparison valid and to fully bring to light any benefits or penalties which may result due to operation of the LMDS system at 40 GHz. Given this assumption, the primary effects of moving to the higher frequency are concentrated in the areas of radio propagation, which in the extremely high frequency (EHF) band are highly dependent on frequency beyond the normal free-space loss effect, and on equipment design and related implementation complexity, which generally increases with increasing frequency.

Summary:

The impact using 40 GHz for the LMDS operation frequency instead of 28 GHz can be summarized as follows: The combined radio propagation and system implementation penalties as a result of operation at 40 GHz can be expected to make LMDS viability highly questionable. This is due to the anticipated increased system cost associated with decreased cell coverage area at 40 GHz versus 28 GHz and the need to establish larger system power margins against occasional effects such as rain, etc. to maintain commercially acceptable service. Additionally, implementation and employment of key system components such as power tubes, solid state sources and subscriber antennas is expected to be much more complex and expensive, and less reliable, at 40 GHz as opposed to 28 GHz. Some of these issues are addressed in more detail below.

Dispersion:

Phase dispersion effects of the channel (causing non-linear phase response) are expected to have a significant impact on the performance of the "return" path data links in the Suite 12 system. Examination of Eb/no degradation due to dispersive effects indicates that degradation is insignificant (less than 1 dB) below 30 GHz and for symbol rates less than half the bandwidth. However, degradation due to nonlinear dispersive effects is expected to increase significantly at carrier frequencies above 35 GHz and may cause unacceptable degradation at 40 GHz, particularly where higher-order modulations are involved (as they will be on the return data links). Adequate performance of these links is vital to the economic viability of the Suite 12 system. For example, phase dispersion is expected to exceed 0.1 radians/km at 40 GHz, while it is virtually insignificant at 28 GHz (Liebe, NTIA Report No. 83-137). Also, and perhaps more important than the magnitude of the dispersion itself, is the fact that the dispersive effect becomes increasingly non-linear with increasing frequency in the bands in question. Thus, operation of the Suite 12 system at 40 GHz will subject transmitted signals to unacceptable levels of nonlinear dispersion, resulting in substantially reduced cell radius at 40 GHz relative to that achievable at 28 GHz, where the effects are not nearly as severe.

Further, because the frequency modulated, interleaved video signals depend on non-linear effects (FM capture, modulation index improvement gain) to provide isolation between adjacent video channels, it is likely that the dispersive effects of operating on near-earth paths at 40 GHz would cause increased mutual interference between video channels and interleaved data channels. (Shanmugan, et.al.; "Wideband Digital Transmission through the Atmosphere at EHF Frequencies: Effects of Refractive Dispersion).

Key Differences between LMDS and Satellite or Point-Point Paths:

Note that the above effects are detrimental to the operation of the Suite 12 system because they are most severe at low altitudes over horizontal paths. This is precisely the type of path over which the Suite 12 system must operate using omnidirectional antennas. Alternatively, satellite systems work on point-point slant paths which may approach zenith, using highly-directional, high-gain antennas. Under these circumstances, the earth-station to satellite path traverses a much lower percentage of low-altitude components. Because of this, satellite systems are much more likely to be successfully operated in the 40 GHz band than the LMDS systems--satellite and other point-point systems can compensate for the additional losses and dispersive effects simply by increasing the antenna gains, resulting in overall improvements in system gain. Care must be taken to examine the key differences in attenuative and dispersive effects at 40 GHz between the near-earth, horizontal paths for LMDS, and the near-zenith paths associated with satellite communications. The disadvantageous effects of operating LMDS at 40 GHz are of sufficient magnitude to threaten its technical and economic viability, while satellite and other point-point services would suffer no such negative effect.

Degradation of Non-LOS LMDS Performance at 40 GHz:

Another key factor in the success of the Suite 12 28 GHz system is the ability to exploit reflection, diffraction, scattering, and passive repeating to reach subscriber areas not on a direct line-of-sight path to a transmitter. The ability to reach subscribers using by exploiting these effects will be reduced if the system is moved from 28 to 40 GHz. The penalty in moving in frequency from 28 to 40 GHz is expected to be particularly severe relative to the diffractive and scattering effects. Due to changes in wavelength relative to fixed propagation geometries and fixed building surface roughness, although exhaustive analysis has not been conducted, I anticipate that the number of subscriber locations serviceable by exploitation of scattering from building surfaces and passive repeating will decrease significantly. In turn, the 40 GHz system will require much higher levels of "special case" engineering design and implementation methods, as well as the use of a larger number of cells to cover a given service area. This will result in a significant increase the capital cost of the LMDS system and degrade its potential as a viable alternative to cable access systems. This is clearly not in the best interest of the consumer or national interest.

By:

Eric N. Barnhart, P.E.
December 13, 1993

Georgia Institute of Technology
Georgia Tech Research Institute

BIOGRAPHICAL SKETCH

BARNHART, ERIC N.--Division Chief
Communications and Networking Division
Information Technology and Telecommunications Laboratory

Education

M.S.E.E., Georgia Institute of Technology	1985
B.E.E., Auburn University	1982

Employment History

Georgia Institute of Technology	
Chief, Communications and Networking Division	1993-Present
Director, Communications Laboratory	1991-1993
Associate Chief, Communications Systems Div.	1989-1990
Head of Communications Countermeasures Branch	1988-1989
Senior Research Engineer	1990-Present
Research Engineer II	1986-1990
Research Engineer I	1983-1986
Martin Marietta Aerospace, Orlando Division	
Engineering Aide	1979-1981

Experience Summary: Has administrative, technical and budget responsibility for the Communications and Networking Division. Presently oversees sponsored programs in commercial telecommunications and military C3I systems and countermeasures. Responsible for the development and management of GTRI systems and technology programs related to these research areas. Is a member of the staff of the Georgia Center for Advanced Telecommunications Technology (GCATT). Currently is involved in the investigation of indoor propagation and the development of Personal Communications Network (PCN) services and equipment. Is also currently involved in development of interactive cable system trial for distance learning. Recently involved in the development of adaptive, spread-spectrum communications systems and techniques. Also investigated cosite interference mitigation techniques. Has conducted vulnerability analysis and testing of multichannel secure communications systems for tactical and strategic applications. Has experience in the performance analysis and operational testing of intercept systems, and foreign equipment exploitation and analysis. Has experience in the analysis and computer modeling of coded, spread-spectrum digital communications systems to investigate system vulnerability with respect to interception and disruption by jamming. Has experience with propagation analysis/modeling from HF through millimeter-wave frequencies, threat evaluation and wideband signal processing. Has hardware design experience with discrete digital systems, and hardware/software development experience with microprocessor based systems. Also has worked on systems integration, calibration, and testing of millimeter-wave radar seeker/guidance systems and temperature control systems. Active as a consultant to government and industry.

Current Fields of Interest

Wireless/personal communications; broadband interactive systems; telecommunications/economic development; networks for enterprise integration, distance learning and telemedicine; multimedia and client-server systems and architectures; military communications; communications privacy/security; telecommunication systems and networks; data communications; lightwave communications; intercept/surveillance systems and techniques; countermeasures systems and techniques; communication system vulnerability; modeling; simulation; signal processing.

Registrations and Special Honors

Registered Professional Engineer, Georgia
General Chairman, 1993 National Telesystems Conference
Wireless Technology Consultant, Sun Features/L.A. Times Syndicate
National Science Foundation Small Business Innovative Research (SBIR) Proposal Review Board in Communications and Networking
Scientific Advisory Board - International Tele-Marine Corporation
Telecommunications Technology Consultant to Caribbean Association of National Telecommunications Organizations (CANTO)
Member: IEEE, IEEE Communications Society, Communications Systems Engineering Committee, Radio Communications Committee, Vehicular Technology Society, Aerospace and Electronic Systems Society; Society of Photo-Optical Instrumentation Engineers; Association of Old Crows; Armed Forces Communications Electronics Association; Tau Beta Pi, Eta Kappa Nu; IVHS America

Major Reports and Publications

1. "An Analysis of Millimeter-Wave Wireless Local Area Networks for LPI/AJ Command Post Communications," Proceedings of the 1993 Military Communications Conference, Boston, Massachusetts, October 1993, coauthor
2. "Distance Learning Via a Caribbean Teleconference Network," Record of the CANTO 1993 Conference and Trade Exhibition, Oranjestad, Dutch Caribbean, June 1993
3. "A Proposed Vocational Education Network: Training, Economic and Technical Implications," Proceedings of the 15th Pacific Telecommunications Conference, Honolulu, Hawaii, January 1993
4. "Trends in Multipath Delay Spread from Frequency Domain Measurements of the Wireless Indoor Communications Channel," Proceedings of the Third International Symposium on Personal, Indoor and Mobile Radio Communications, Boston, Massachusetts, October 1992, coauthor
5. "Mathematical Expressions and Algorithms for Cell Evaluation Tool," Final Report, Project A-9065-200, September 1992, coauthor
6. "Interim Technical Report Number 1: Experimental Licenses KK2XBA and KK2XBB," Interim Report, Federal Communications Commission, August 1992, coauthor

7. "Georgia: Well-Positioned for the Telecommunications Revolution," Computer Currents Magazine, Vol. 4, No. 8, August 1992
8. "Prototype Implementation of an EHF Switched-Beam Array Controller," Final Report, Project A-8200, August 1992, coauthor
9. "Propagation Characterization in Support of BellSouth Personal Communications Services Development," Final Report, Project A-9041, April 1992, coauthor
10. "Propagation Measurements in Support of Hitachi Wireless Communications Model Development," Final Report, Project A-9065-100, March 1992, coauthor
11. Full Speed Ahead for Wireless Access Systems," Guest Expert Section, Computer Currents Magazine, Vol.3, No.10, October 1991
12. "Statistical Data from Frequency Domain Measurements of the Indoor PCN Communication Channel," Proceedings of the IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, London, England, United Kingdom, September 1991, coauthor
13. "Test Plan for Hitachi In-Building Communications Channel Characterization," Interim Report, Project B-699, August 1991, coauthor
14. "GUARDRAIL/Common Sensor Upgrade and Environment Analysis," Final Report, Project A-8418, June 1991, coauthor
15. "Electronic Warfare Vulnerability Assessment Process Demonstration Design," Proceedings of the Georgia Tech ECCM Workshop, Atlanta, Georgia, April 1991, coauthor
16. "Characterization of Propagation in Support of Personal Communications Services Development," Final Report, Project A-8756, April 1991, coauthor
17. "Advances in Wireless Communications Systems and Technology," Conference Record of SOUTHCON/'91, Atlanta, Georgia, March 1991
18. "Characterization of Indoor Propagation for Personal Communications Services," Conference Record of SOUTHCON/'91, Atlanta, Georgia, March 1991, coauthor
19. Equipment Design and Measurement Plan for Propagation Characterization in Support of Personal Communications Services Development," Interim Report, Project A-8756, November 1990, coauthor
20. "EHF Switched-Beam Array Design" Interim Report, Project A-8200, November 1990, coauthor
21. "Independent Assessment of Radio Propagation Losses in the Raytheon C1 Model and the CECOM MSE and JTIDS System Performance Models," Final Report, Project A-8653, August 1990, coauthor
22. "Millimeter Waves for Communications," International Conference on Millimeter-Wave and Far-Infrared Technology, Beijing, China, June 1990
23. "Millimeter-Wave Antennas and Receivers," Final Report, Project A-4070-400, May 1990, coauthor
24. "EURODEMO Data Analysis," Final Report, Project A-8373, March 1990
25. "Millimeter Wave Direction Finding Using Switched-Beam Array Technology," 14th International Conference on Infrared and Millimeter Waves, Wurzburg, West Germany, October 1989
26. "Application of ACT Devices To Cosite Interference Reduction", Final Report, ECSL Internal Research, September 1989, coauthor

27. "Switched-Beam Array Antenna, "Interim Report, Project A-4070-400, June 1989, coauthor
28. "Analysis of REGENCY NET Access by a Follower Jammer," Final Report, Project A-8191, May 1989, coauthor
29. "REGENCY NET Jamming Vulnerability Issues and Electromagnetic Compatibility Tests," Interim Report, Project A-8191, March 1989, coauthor
30. "REGSIM Evaluation Results," Interim Report, Project A-8191, January 1989, coauthor
31. "Cosite Interference Reduction," Final Report, Project A-8063, January 1989, coauthor
32. "Specialized Engineering for Special Operations Forces," Final Report, Project A-4965, November 1988, coauthor
33. "Adaptive Signal Masking Techniques," 1988 Military Communications Conference, San Diego, CA, October 1988, coauthor
34. "Susceptibility Testing of an HF, Multichannel, Secure Communications System," Final Report, Project A-4526, April 1988, coauthor
35. "JTIDS Siting Analysis," Final Briefing, Project A-4918-200, April 1988, coauthor
36. "Avionics Configuration Analysis Program (ACAP)--Functional Description," Interim Report, Project A-4965-700, April 1988, coauthor
37. "Adaptive Signal Masking Techniques," Interim Report, Project A-4626, February 1988, coauthor
38. "Air-to-Air Applications for Millimeter-Wave Communications," 12th Annual International Conference on Infrared and Millimeter Waves, Orlando, Florida, December 1987
39. "Millimeter-Wave Communications: Air-to-Air Applications," 1987 SPIE Technical Symposium Southeast, Orlando, Florida, May 1987
40. "VALLTOSE Program," Final Report, Project A-4427, January 1987
41. "Direction Finding Capabilities," Final Report, Project A-4216, June 1986, coauthor
42. "Adaptive Thresholding: A Detection Technique for Wideband Large-Sector Intercept Systems," 1986 Tactical Communications Conference, Ft. Wayne, Indiana, April 1986
43. "GRANITE ICE Communications Equipment Exploitation and Analysis," Final Report, Project A-4227, March 1986, coauthor
44. "VALLTOSE Task 1: Detection Techniques," Final Report, Project A-4029, November 1985, coauthor
45. "An Examination of the LPI Characteristics of EHF Air-to-Air Communications Systems," 1985 Military Communications Conference, Boston, Massachusetts, October 1985, coauthor
46. "Evaluation of the AJ/LPI Performance of an EHF Air-to-Air Communications System," Final Report, Project A-4041, May 1985, coauthor
47. "Threat Evaluation for JTIDS Radios Used for PATRIOT Communications," Final Report, Project A-3936, January 1985, coauthor
48. "ABIT Data Link Threat Assessment," Final Report, Project A-3054-420, January 1985, coauthor
49. "Performance of EHF Communications Systems in the Presence of Jamming," 1984 Military Communications Conference, Los Angeles, California, October 1984, coauthor

APPENDIX 4

DAVID SARNOFF RESEARCH CENTER STUDY
BY R. L. CAMISA

12/15/93

Memo to: B. B. Bossard

From: R. L. Camisa
David Sarnoff Research Center
201 Washington Rd
Princeton N.J. 08543

Subject: Comparison of LMDS at 28 and 42 GHz

We recalculated the LMDS range at 28 and 42 GHz using the rain model in the 1982 CCIR Report 338-4, paragraph 5.2. The new input data at 28 and 42 GHz are:

Frequency (GHz)	28	42
Availability (%)	99.9	99.9
Rain Rate (mm/hr)	52.4	52.4
Effective Diameter of Transmit Antenna (inches)	0.545	0.365
Effective Diameter of Receive Antenna (inches)	6.9	4.6
Receiver Noise Figure (dB)	6	8
Receiver Noise Bandwidth (MHz)	18	18
Minimum Carrier-to-Noise Ratio (dB)	13.4	13.4
Number of Carriers	50	50
TWTA Backoff (dB)	7	7

The transmit antenna is omnidirectional with a gain of 10 dB; the receive antenna is directional with 32 dB of gain. The rain rate is modeled after New York City. These data are identical to those use in the September 17, 1991 Sarnoff Report. Note the number of carriers was also increased to 50.

Figure 1 shows the attenuation due to rain as a function of the distance between the transmit antenna and the receiver antenna. At a range of 3 miles, the attenuation varies from 15.2 dB at 28 GHz to 22.5 dB at 42 GHz; that is, there is a 7.3 dB increase in attenuation due to the rain. Figure 2 shows the same effect in a different way by looking at the required TWTA saturated output power. If you take the point at which the TWTA output power is 78 watts, then the available coverage range at 28 GHz is out to 3 miles; but at 42 GHz the coverage range is only out to 1.7 miles. So, you are correct, then, in saying that the effective coverage range at 42 GHz is about half the range at 28 GHz due to the increase in path loss and rain fade at the higher frequency. This will definitely translate to a need for more transmitters to cover the same service area, which obviously will increase the overall cost. Also at 40 GHz TWTAs are lower performance and higher cost. Our vendors indicate that the best output power achievable today at 42 GHz is in the range of 50 watts, and that the gain is typically 6 dB lower than at 28 GHz. The degradation in performance as well as the increase in technical complexity will have a profound impact on transmitter costs.

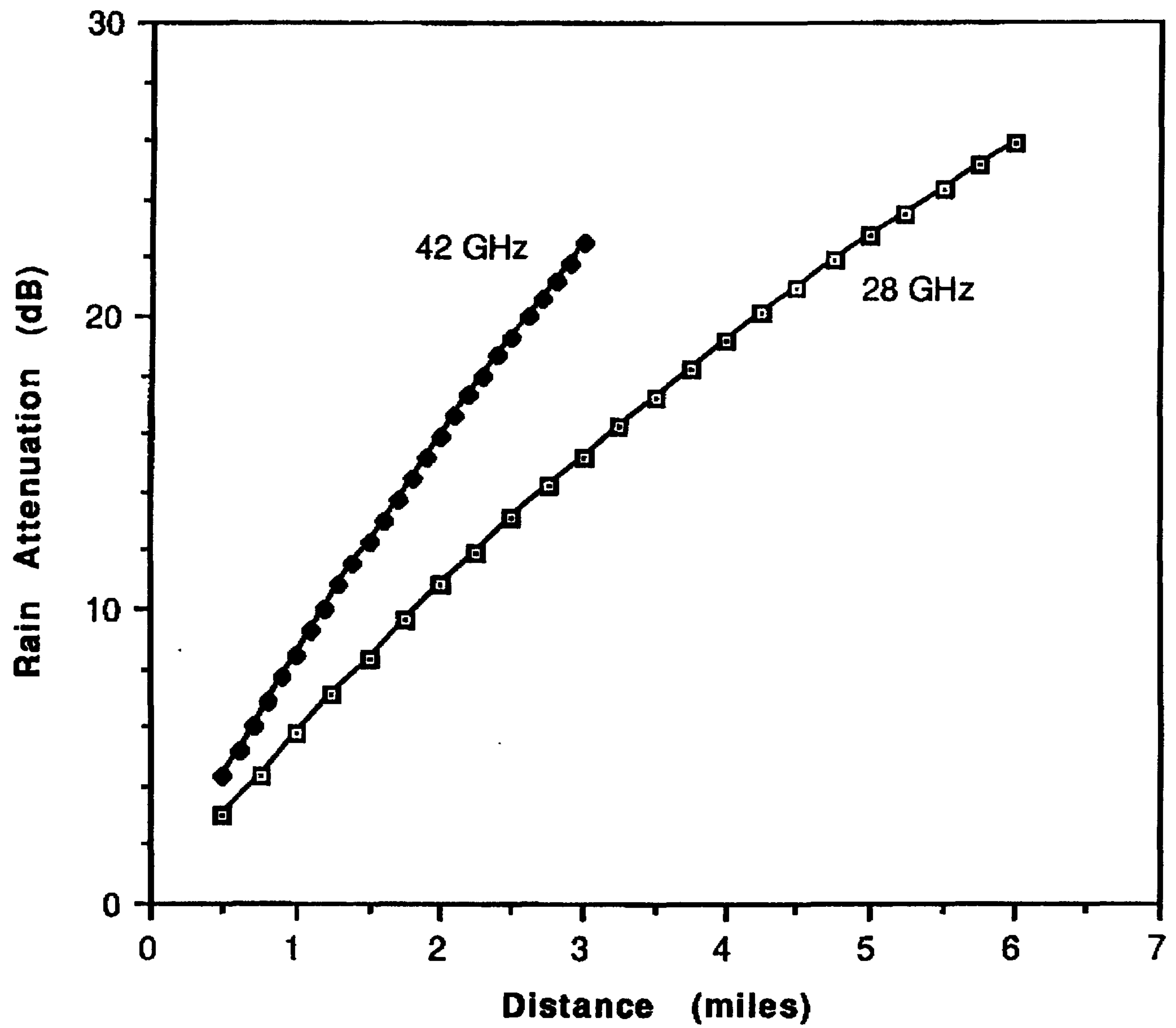
I believe that your estimate of receiver costs at 42 GHz being 30% higher than at 28 GHz are probably in the ballpark. More LNA stages will be necessary to compensate for the decrease in device gain, all dimensions will be smaller which will increase the amount of assembly labor, etc.

The U.S. Department of Commerce, National Telecommunications and Information Administration published a report in October of 1989 entitled, "Vegetation Loss Measurements at 9.6, 28.8, 57.6 and 96.1 GHz Through a Conifer Orchard in Washington State." The report number is NTIA 89-251. Section 4.3.1 of that report details the vegetation loss through foliage at various tree depths and several different paths. This data is reproduced herein as Figs. 3, 4, 5, and 6. The two curves in each figure are for different elevations of the transmitter-receiver path above the ground; that is, 3 and 5 meters. At the 5-meter height, there is an increase in loss of about 7 dB going from 28.8 to 57.6. The loss at 42 GHz should not be quite that high but it will still be on the order of 3 dB.

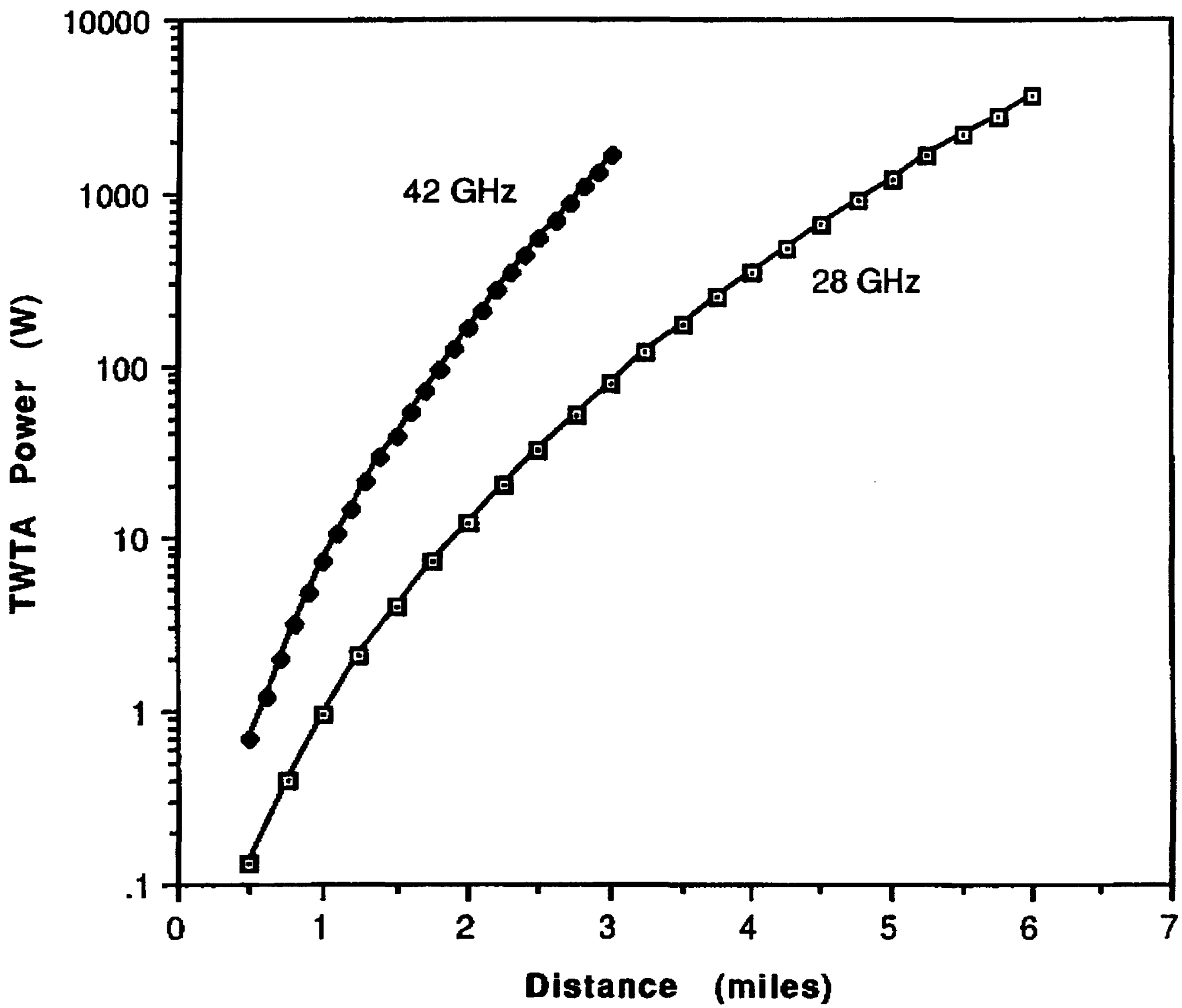
As far as the decrease in the number of channels due to increasing the bandwidth to 27 MHz, there are many tradeoffs that would have to be evaluated before making such a broad statement.

The roughness factor for scattering the signal at 42 GHz will be higher. The effect will be a reduction in the signal strength of a reflected signal.

Sarnoff would have to agree with your conclusion that the 40 GHz band is less economical and requires a major advancement in the state-of-the-art of tube technology when compared to 28 GHz. Receivers will also be lower performance and higher cost.



30
20
10
0
Rain Attenuation (dB)
42 GHz
28 GHz
0
1
2
3
4
5
6
7
Distance (miles)



42 GHz
28 GHz
TWTA Power (W)
10000
1000
100
10
1
.1
0
1
2
3
4
5
6
7
Distance (miles)

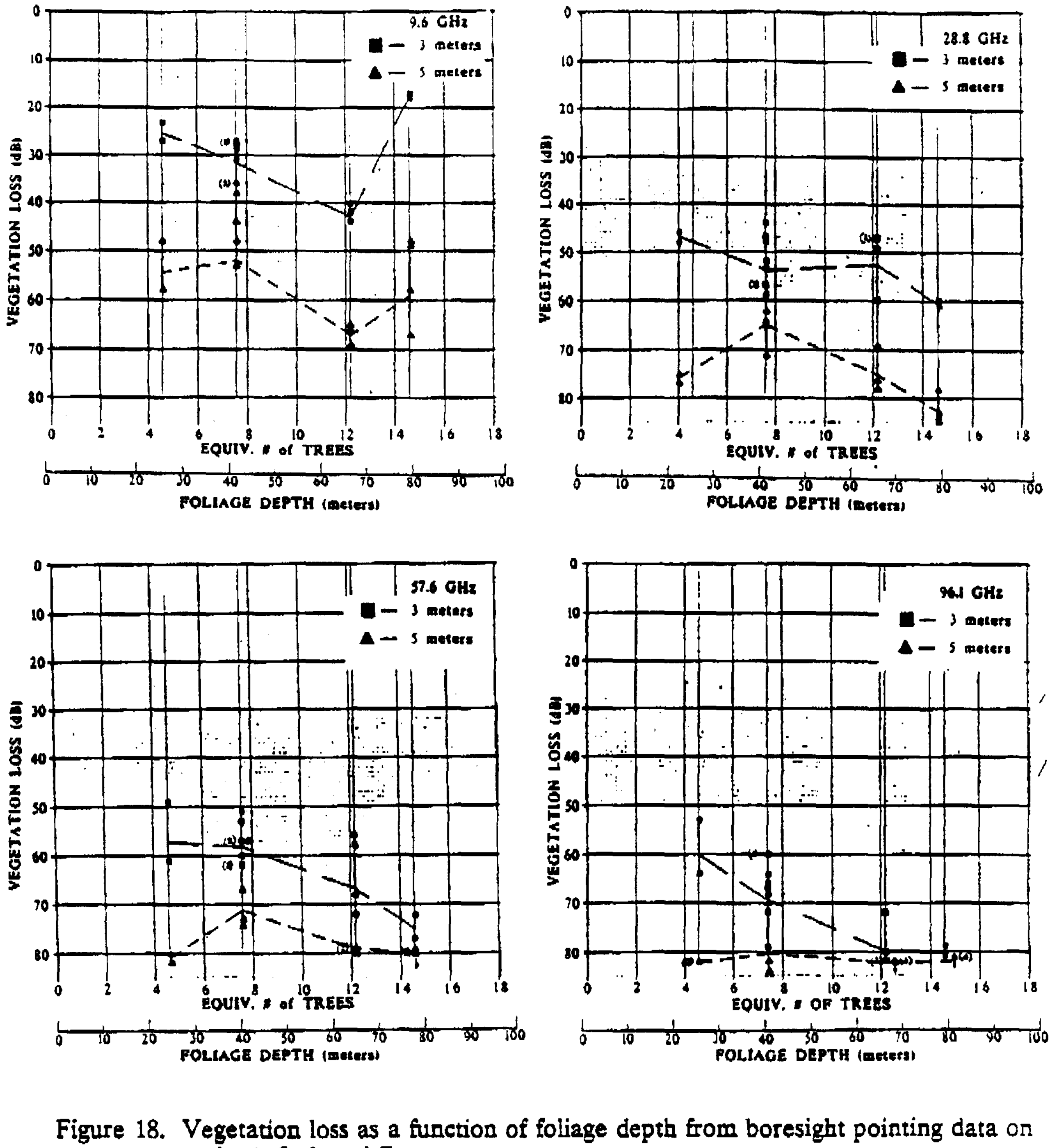


Figure 18. Vegetation loss as a function of foliage depth from boresight pointing data on paths 4, 5, 6, and 7.

Press Reports

THE WALL STREET JOURNAL
MARKETPLACE
Reprinted-Friday, December 11, 1992

MARKET & MEDIA

FCC Proposes Using New Technology To Send Video and Voice by Airwaves

By MARY LU CARNEVALE
Staff Reporter of THE WALL STREET JOURNAL

WASHINGTON – The Federal Communications Commission proposed using airwaves to deliver video and voice in what could be competition for both cable television and local telephone monopolies.

The new technology could open the way for local telephone companies to provide two-way video services and other advanced telecommunications – including movies on demand, video teleconferencing, and telecommuting services. Other companies, such as cable TV operators, could turn around and use the technology to compete with phone companies.

"The full potential of this technology has yet to be explored," said Robert Pepper, head of the FCC's Office of Plans and Policy. "But it holds the very exciting prospect of introducing new services in both the video and the telecommunications marketplaces."

The commission voted, 5-0, to seek public comment on its plan to set up the service in the 28 gigahertz band – a frequency that once was considered too high to be useful. Under the FCC plan, licenses would be awarded to two operators in each of 489 regions across the country. Every operator would receive a 1000 megahertz block of spectrum.

The plan grew out of a request by Suite 12 Group, a Freehold, N.J., partnership, that developed a system to deliver high-quality video over a network that uses microcells to transmit signals to a flat, four-square-inch antenna mounted either inside or outside a house window. The partnership recently began offering 49 channels of cable TV programming in Brooklyn's Brighton Beach neighborhood for $29.95 a month, according to the company.

Shant Hovnanian, a company partner, said the system can be installed for about $350 a subscriber, less than half the cost of building a typical cable TV system, and a fraction of the cost of stringing optical fiber to homes. The system, known as Cellularvision, is based on patented technology invented by Bernard Bossard, another partner.

Several telephone company and cable TV officials reached yesterday said that Suite 12's technology and the FCC action was a surprise. "We've tried to keep it quiet until the FCC vote," Mr. Hovnanian said, adding that contentious Washington proceedings can stifle new technology.

Eventually, Mr. Hovnanian said, compression technology, which shrinks the amount of data needed to transmit video signals, would permit video cellular systems to carry hundreds of channels. Subscribers could be linked through phone lines or cable networks to "video jukeboxes" that store thousands of movies, TV programs and other offerings.

The FCC also voted to award Suite 12 a so-called pioneer's preference—a licensing advantage given to companies that create services. But the award was for the license Suite 12 already holds for the New York area, rather than the license it sought for Los Angeles.

Separately, the agency proposed adopting a Motorola Inc. system as the standard for AM-radio stereo broadcasting. The FCC said that about 660 of the nation's 5,000 AM stations already have converted to stereo and that 90% of the stereo stations use the Motorola system.

The commission was directed under a new law to adopt a single AM stereo standard, and the proposal is the first step in that process. Under the proposal, stations using other stereo systems would have to stop using them a year after the rules go into effect next year.

The New York Times

FRONT PAGE

Reprinted From Friday, December. 11, 1992

A New Microwave System Poses Threat to Cable TV

By EDMUND L. ANDREWS

Special to The New York Times

WASHINGTON, Dec. 10 — The Federal Communications Commission approved a new microwave technology today to transmit simultaneously dozens of channels of television, telephone calls and large amounts of data.

The system, which would use superhigh-frequency radio signals to deliver up to 49 television channels, could pose a threat to the virtual monopoly that cable television systems enjoy today in most cities. The system was recently introduced, on an experimental basis, to homes in Brighton Beach, Brooklyn.

One big advantage to the technology is that it avoids the need to spend millions of dollars to lay cables to every home in a city, a cost that is passed on to cable television subscribers.

Once Considered Unusable

The main innovation of the new technology is its use of extremely high-frequency microwaves to transmit information. Until now, these radio frequencies — far higher than the UHF and VHF signals commonly used in television broadcasting — have been considered unusable for anything more than transmitting data between two sites in full view of each other.

The new technology was developed by a Freehold, N.J., start-up company called Cellular Vision of New York Inc. Company officials said the technology would make it possible to undercut, by more than half, the prices of cable television companies, which deliver their signals over wires.

Impressed by the results from two years of technical tests, the F.C.C. today proposed allocating a big block of superhigh radio frequencies for the new technology and offering licenses to two companies in each market. Recognizing Cellular Vision as the pioneer, the commission tentatively gave it the chance to choose between a license for the metropolitan New York or Los Angeles areas. Licenses for other markets will probably be issued through a lottery process, perhaps as soon as next summer.

The developers of the technology assert that they can reach almost every site in a metropolitan area, in part by bouncing signals off buildings and other objects until they reach their ultimate destination.

In Brighton Beach, the company began offering a package of

Reprinted from:

Broadcasting

Technology

FM WIRELESS TV TO BITE THE APPLE

CellularVision commits $20 million-plus to N.Y. expansion

By Peter Lambert

A startup company in Brighton Beach, N.Y. (Brooklyn), has taken much of the television industry by surprise this past week, bringing a new cellular, multichannel TV-voice-data player into the mix of cable, broadcast, multipoint microwave (MMDS), local exchange and satellite competitors. Still absorbing the news about Local Multipoint Distribution Service (LMDS), those competitors remain open but skeptical about its potential impact.

Last Monday (Dec. 15), with a proposed spectrum allocation and pioneer preference from the FCC in hand, CellularVision (CV) of New York committed more than $20 million to expand its 49-channel, wireless TV service now operating in the 28 ghz frequency band in Brighton Beach, ordering 100,000 consumer antennas and converter boxes.

The reverse-polarity FM technology offers up to 98 one-way video channels or a mix of one and two-way services. CV, which will franchise its system to operators nationwide, believes the hardware is highly cost competitive from day one.

CV will target the New York area with services including video on demand, interactive and high-definition TV, high-speed data, personal communications, telephone and educational services. "We expect to compete successfully with existing cable television providers because we offer higher-quality television transmissions at lower prices," says CV partner Shant Hovnanian.

However, CellularVision inventor and partner Bernard Bossard believes competitiveness with cable "is being overplayed. Our two-way capabilities may make us complementary with cable."

CV did not disclose the terms of its contracts with MA/Com Inc. and Alpha Industries for antennas and with Hughes Aircraft and Catel Corp. for transmitters. But with each antenna receiver unit running about $260, the order may approach $26 million. When a smart-card encryption system is integrated into the receiver by next spring, the unit price will rise to about $350.

CV plans to own and install 5,000 units by the end of March 1993. Given approval of the FCC's 27.5-29.5 ghz band allocation for LMDS and its proposal to license two operators in each of 489 cellular service areas nationwide (BROADCASTING, Dec. 14), CV will seek other licenses. More than 950 LMDS applications were thrown out until a lottery or other licensing procedure is implemented.

The hardware comprises a satellite downlink; omni-directional transmitter; 4-by-4-inch receive antennas mounted on subscriber windowsills, and set-top tuners. The company claims its per-subscriber construction, operating and maintenance costs will run under $500, compared with more than $3,000 for fiber optic; $2,000 for cable; $1,000 for DBS, and $750 for standard multichannel multipoint distribution service (MMDS), or wireless cable.

CV launched last June, offering a $25.95 basic package of 39 cable programming services; $29.95 with Showtime and The Movie Channel. Although Turner Broadcasting has been reluctant to offer TNT, Bossard says, overall, access to programming has not been an issue, as it negotiates carriage of HBO, The Disney Channel, regional sports and pay-per-view services.

Inventor Bernard Bossard and partner Shant Hovnanian predict 5,000 subscriptions by spring.

The proposed rulemaking does not rule out existing cable or local telephone companies from LMDS cross-ownership. But, at least on first blush, several cable executives pointed to line-of-sight difficulties and the threat of rain fade at high frequencies as reasons to be skeptical about the 28 ghz service.

However, Bossard says rain fade is already figured into the 28.5-square mile cell size. As for line of sight, while FM transmission allows relatively ghostless reception off of buildings, CellularVision plans to use reflectors or "very low cost repeaters, about $700 each" to create microcells and fill in line-of-sight gaps.

Even so, Bossard concedes, "it would take a fortune" to make the service available to 90% of service area residents within three years, as the FCC proposes.

In an open letter dated Dec. 10, the Competitive Cable Association said: "This new action by the commission is no small adventure. There are about 100 video-size channels (each about 20 mhz) in the band 27.5-29.5 ghz. That should be enough to cure the problem that has so far impeded wireless cable."

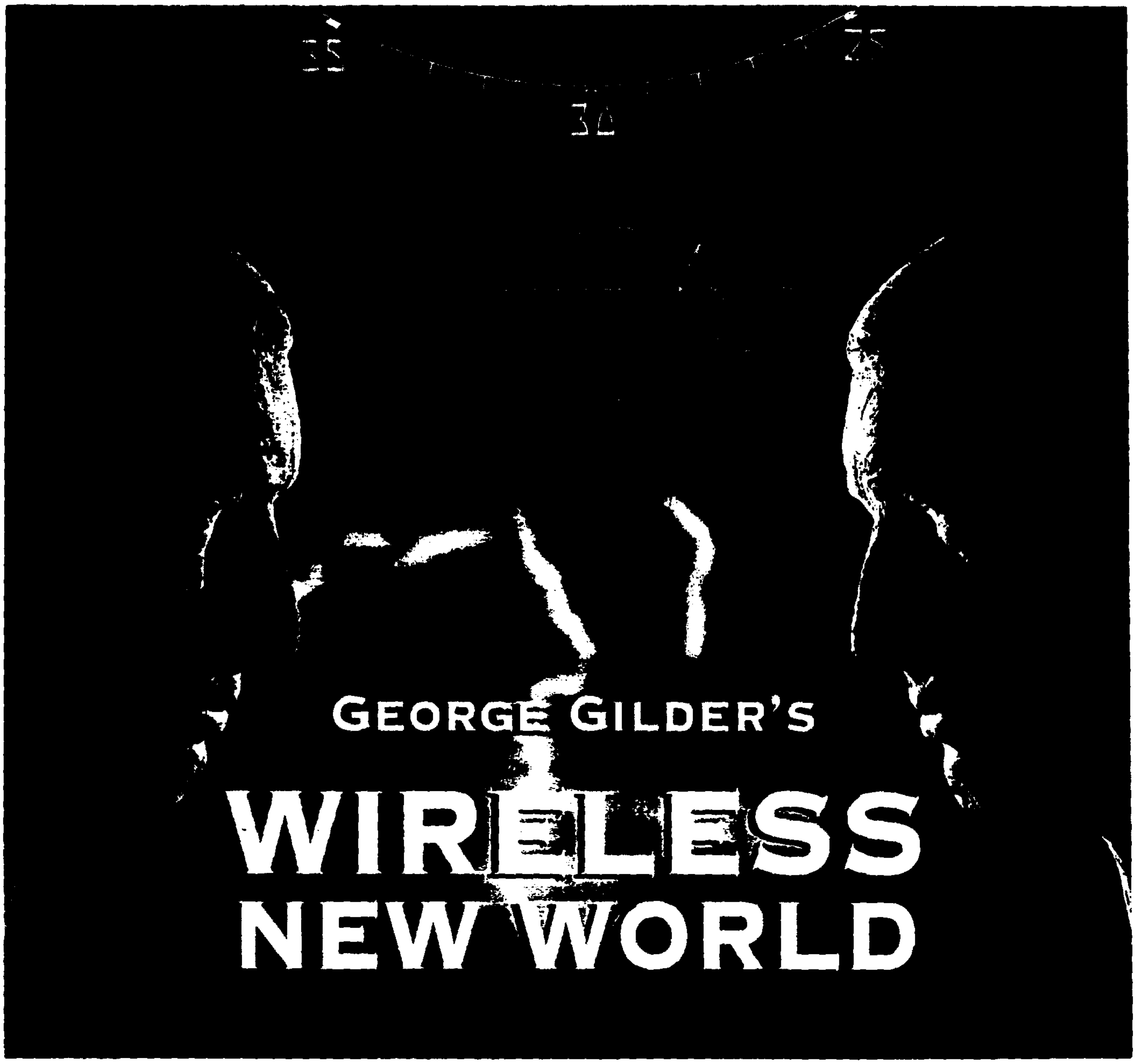
Noting that "to date, this is only a single-cell test," Wireless Cable Association President Robert Schmidt says if LMDS truly affords competition in video, voice and data, WCA members "will line up" with other license applicants.

However, Schmidt adds, "so far, all the research and manufacturing are in AM. We're doing this today, and our cell reaches 50 miles."

By early January, he adds, WCA will begin sharing encouraging results from digital MMDS field tests in San Bernadino, Calif. Top cable operator Tele-Communications Inc.'s $200 million commitment to digital channel expansion (BROADCASTING, Dec. 7) "says the train will leave the station," Schmidt says. "We intend to be on that train." ■

A Technology Supplement to Forbes Magazine

Forbes ASAP



GEORGE GILDER'S

TELECOSM

"The New Rule of Wireless"

AT FIRST GLANCE, Vahak Hovnanian, a homebuilding tycoon in New Jersey, would seem an unlikely sort to be chasing rainbows. Yet in the converging realms of computers and communications that we call the telecosm, rainbows are less a matter of hue and weather than they are a metaphor for electromagnetism: the spectrum of wavelengths and frequencies used to build businesses in the Information Age.

An Armenian Christian from Iraq, Hovnanian ran a business building high-quality "affordable" housing. His first coup came on Labor Day in 1958 when, together with his three older brothers, he bought an apparently undesirable property near the waterfront in Tom's River for $20,000. From this modest beginning has arisen not only one of the nation's largest homebuilding enterprises (divided among the four immigrant brothers), but also a shattering breakthrough on some seemingly bleak frontiers of the electromagnetic spectrum. Together with maverick inventor Bernard Bossard, Hovnanian has launched a wireless cellular TV business in frequencies once thought usable only in outer space.

Perhaps the reason Hovnanian feels comfortable today pioneering on the shores of the telecosm is that some 35 years ago he was an engineer at Philco Semiconductor following in the theoretical steps of AT&T Bell Laboratories titan William Shockley. Shockley led the team that plunged into the microcosm of solid-state physics and invented the transistor. At the heart of all-digital electronics, this invention still reverberates through the world economy and imposes its centrifugal rules of enterprise.

This law of the microcosm dictates exponential rises in computer efficiency as transistors become smaller. It is this law that drives the bulk of the world's computations to ever-cheaper machines and pushes intelligence from the center to the fringes of all networks. Today the microcosm is converging with the telecosm and igniting a new series of industrial shocks and surprises.

The convergence of microcosm and telecosm in an array of multimedia industries—from personal intelligent communicators to video teleputers to digital films and publishing—is now the driving force of world economic growth. John Sculley, chairman and CEO of Apple Computer, has projected that by 2002 there will be a global business in multimedia totaling some $3.5 trillion—close to the size of the entire U.S. economy in the early 1980s.

This new world of computer communications will break down into two domains—the fibersphere and the atmosphere. The fibersphere is the domain of all-optical networks, with both communications power—bandwidth—and error rate improving by factors in the millions. In "Into the Fibersphere" (Forbes *ASAP*, December 7, 1992), we saw that the potential capacity for communications in the fibersphere is 1,000 times greater than all the currently used frequencies in the air—and so radically error-free that it mandates an entirely new model of wired telecommunications. Now we will discover that the atmosphere will offer links as mobile and ubiquitous as human beings are. It thus will force the creation of an entirely new model of wireless networks.

In one sense, Sculley's $3.5 trillion dream can be seen as the pot of gold at the end of Maxwell's rainbow. In 1865, in a visionary coup that the late Richard Feynman said would leave the American Civil War of the same decade as a mere "parochial footnote" by comparison, Scottish physicist James Clerk Maxwell discovered the electromagnetic spectrum. Encompassing nearly all the technologies imagined by Sculley, Maxwell's rainbow reaches from the extremely low frequencies (and gigantic wavelengths) used to communicate with submarines all the way through the frequencies used in radio, television and cellular phones, on up to the frequencies of infrared used in TV remotes and fiber optics, and beyond that to visible and ultraviolet light and X-rays. In a fabulous feat of unification, Maxwell reduced the entire spectrum to just four equations in vector calculus. He showed that all such radiations move at the speed of light—in other words, the wavelength times the frequency equals the speed of light. These equations pulse at the heart of the information economy today.

Virtually all electromagnetic radiation can bear information, and the higher the frequencies, the more room they provide for bearing information. As a practical matter, however, communications engineers have aimed low, thronging the frequencies at the bottom of the spectrum, comprising far less than one percent of the total span.

> *Such an explosion of efficiency radically limits the need to waste watts in order to overcome noise. More communications power comes from less electrical power. Thus, Shannon shows the way to Sculley's vision.*

The vast expansion of wireless communications forecast by Sculley, however, will require the use of higher frequencies far up Maxwell's rainbow. This means a return to the insights of another great man who walked the halls of Bell Labs in the late 1940s at the same time as future Nobel laureate William Shockley, and who left the world transformed in his wake.

In 1948, the same year that Shockley invented the transistor, Claude Shannon invented the information theory that underlies all modern communications. At first encounter, information theory is difficult for nonmathematicians, but computer and telecom executives need focus on only a few key themes. In defining how much information can be sent down a noisy channel, Shannon showed that engineers can choose between narrowband high-powered solutions and broadband low-powered solutions.

From Long & Strong to Wide & Weak

Assuming that usable bandwidth is scarce and expensive, most wireless engineers have strived to economize on it. Just as you can get your message through in a crowded room by talking louder, you can overcome a noisy channel with more powerful signals. Engineers therefore have pursued a strategy of long and strong: long wavelengths and powerful transmissions with the scarce radio frequencies at the bottom of the spectrum.

Economizing on spectrum, scientists created mostly analog systems such as AM radios and televisions. Using every point on the wave to convey information and using high power to overcome noise and extend the range of signals, the long and strong approach seemed hugely more efficient than digital systems requiring complex manipulation of long strings of on-off bits.

Ironically, however, the long and strong policy of economizing on spectrum led to using it all up. When everyone talks louder, no one can hear very well. Today, the favored regions at the bottom of the spectrum are so full of spectrum-hogging radios, pagers, phones, television, long-distance, point-to-point, aerospace and other uses that heavy-breathing experts speak of running out of "air."

Shannon's theories reveal the way out of this problem. In a counterintuitive and initially baffling redefinition of the nature of noise in a communications channel, Shannon showed that a flow of signals conveys information only to the extent that it provides unexpected data—only to the extent that it adds to what you already know. Another name for a stream of unexpected bits is noise. Termed Gaussian, or white, noise, such a transmission resembles random "white" light, which cloaks the entire rainbow of colors in a bright blur. Shannon showed that the more a transmission resembles this form of noise, the more information it can hold.

Shannon's alternative to long and strong is wide and weak: not fighting noise with electrical power but joining it with noiselike information, not talking louder but talking softer in more elaborate codes using more bandwidth. For example, in transmitting 40 megabits per second—the requirement for truly high-resolution images and sounds—Shannon showed some 45 years ago that using more bandwidth can lower the needed signal-to-noise ratio from a level of one million to one to a ratio of 30.6 to one. This huge gain comes merely from increasing the bandwidth of the signal from two megahertz (millions of cycles per second) to eight megahertz. That means a 33,000-fold increase in communications efficiency in exchange for just a fourfold increase in bandwidth.

Such an explosion of efficiency radically limits the need to waste watts in order to overcome noise. More communications power comes from less electrical power. Thus, Shannon shows the way to fulfill Sculley's vision of universal low-powered wireless communications.

This vision of wide and weak is at the heart of the most promising technologies of today, from the advanced digital teleputer sets of American HDTV to ubiquitous mobile phones and computers in so-called personal communications networks (PCNs). Shannon's theories of the telecosm provide the basic science behind both Sculley's dream and Hovnanian's video spectrum breakthrough.

Shannon's world, however, is not nirvana, and there is no free lunch. Compensating for the exponential rise in communications power is an exponential rise in complexity. Larger bandwidths mean larger, more complex codes and exponentially rising burdens of computation for the decoding and error-correcting of messages. In previous decades, handling 40 megabits per second was simply out of the question with existing computer technology. For the last 30 years, this electronic bottleneck has blocked the vistas of efficient communication opened by Shannon's research.

> Air delivery of cable television programming had long seemed unpromising. Not only was there too little spectrum available to compete with cable, but what spectrum there was, was guarded by the FCC.

In the 1990s, however, the problem of soaring complexity has met its match—and then some—in exponential gains of computer efficiency. Not only has the cost-effectiveness of microchip technology been doubling every 18 months but the pace of advance has been accelerating into the 1990s. Moreover, the chips central to digital communications—error correction, compression, coding and decoding—are digital signal processors. As we have seen, the cost-effectiveness of DSPs has been increasing—in millions of computer instructions per second (MIPS) per dollar—some tenfold every two years.

This wild rush in DSPs will eventually converge with the precipitous plunge in price-performance ratios of general-purpose microprocessors. Led by Silicon Graphics' impending new TFP Cray supercomputer on a chip, Digital Equipment's Alpha AXP device and Hewlett Packard's Precision Architecture 7100, micros are moving beyond 100-megahertz clock rates. They are shifting from a regime of processing 32-bit words at a time to a regime of processing 64-bit words. This expands the total addressable memory by a factor of four billion. Together with increasing use of massively parallel DSP architectures, these gains will keep computers well ahead of the complexity problem in broadband communications.

What this means is that while complexity rises exponentially with bandwidth, computer efficiencies are rising even faster. The result is to open new vistas of spectrum in the atmosphere as dramatic as the gains of spectrum so far achieved in the fibersphere.

Attacking Through the Air

Hovnanian's campaign into the spectrum began when a cable company announced one day in 1985 that under the Cable Act of 1984 and franchise rights granted by local governments, it had the right to wire one of his housing developments then under construction. Until that day, Hovnanian's own company could package cable with his homes through what are called satellite master antenna TV systems. In essence, each Hovnanian development had its own cable head end where programs are collected and sent out to subscribers.

When the cable company, now Monmouth Cable Vision, went to court and its claim was upheld by a judge, Hovnanian sought alternatives. First he flirted with the idea of having the phone company deliver compressed video to his homes. In 1986, in the era before FCC Commissioner Alfred Sikes, that was both illegal and impractical. Then he met Bernard Bossard and decided to attack through the air. An early pioneer in microchips who had launched a semiconductor firm and eventually sold it to M/A COM, Bossard was familiar with both the soaring power of computers and the murky problems of broadband noise that have long restricted the air to a small number of broadcast AM TV stations.

Air delivery of cable television programming had long seemed unpromising. Not only was there too little spectrum available to compete with cable, but what spectrum there was, was guarded by the FCC and state public utilities commissions.

Nonetheless, in the early 1990s "wireless cable" did become a niche market, led by Microband Wireless Cable and rivals and imitators across the land. Using fragments of a frequency band between 2.5 and 2.7 gigahertz (billions of cycles per second), Microband, after some financial turmoil, now profitably broadcasts some 16 channels to 35,000 New York City homes in line of sight from the top of the Empire State Building. As long as they are restricted to a possible maximum of 200 megahertz and use AM, however, wireless firms will not long be able to compete with the cable industry. Cable companies offer an installed base of potential gigahertz connections and near universal coverage.

Having spent much of his life working with microwaves for satellites and the military, Bossard had a better idea. He claimed he could move up the spectrum and pioneer on frontiers of frequency between 27.5 and 29.5 gigahertz, previously used chiefly in outer space. That would mean he could command in the air some half a million times the communications power, or bandwidth, of typical copper telephone links, some ten times the bandwidth of existing wireless cable, some four times the bandwidth of the average cable industry coaxial connection, and twice the bandwidth of the most advanced cable systems.

The conventional wisdom was that these microwaves (above about 12 gigahertz) are useless for anything but point-to-point transmissions and are doubtful even for these. For radio communication, the prevailing folklore preferred frequencies that are cheap to transmit long distances and that can penetrate buildings and tunnels, bounce off the ionosphere or scuttle across continents along the surface of the earth. The higher the frequency, the less it can perform these feats essential to all broadcasting—and the less it can be sent long distances at all.

Moreover, it was believed, these millimeter-sized microwaves not only would fail to penetrate structures and other obstacles but would reflect off them and off particles in the air in a way that would cause hopeless mazes of multipath. Multipath would be translated into several images, i.e., ghosts, on the screen.

Finally, there was the real show-stopper. Everyone knew that these frequencies are microwaves. The key property of microwaves, as demonstrated in the now ubiquitous ovens, is absorption by water. Microwaves cook by exciting water molecules to a boil. Microwave towers are said to kill birds by irradiating their fluids. Microwave radar systems won't work in the rain. Mention microwaves as a possible solution to the spectrum shortage, and everyone—from editors at *Forbes* to gurus at Microsoft, from cable executives to Bell Labs researchers—laughs and tells you about the moisture problem.

So it was no surprise that when in 1986 Bossard went to M/A COM and other companies and financiers with his idea of TV broadcasting at 28 gigahertz, he was turned down flat. Amid much talk of potential "violations of the laws of physics," jokes about broiling pigeons and warnings of likely resistance from the FCC, he was spurned by all. In fairness to his detractors, Bossard had no license, patent or prototype at the time. But these holes in his plan did not deter Vahak Hovnanian and his son Shant from investing many millions of dollars in the project. It could be the best investment the Hovnanian tycoons ever made.

The new rule of radio is the shorter the transmission path, the better the system. Like transistors on semiconductor chips, transmitters are more efficient the more closely they are packed together.

New Rule of Radio

For 35 years, the wireless communications industry has been inching up the spectrum, shifting slowly from long and strong wavelengths toward wide and weak bands of shorter wavelengths. Mobile phone services have moved from the 1950s radio systems using low FM frequencies near 100 megahertz, to the 1960s spectrum band of 450 megahertz, to the current cellular band of 900 megahertz accommodating more than 10 million cellular subscribers in the U.S.

During the 1990s, this trend will accelerate sharply. Accommodating hundreds of millions of users around the world, cellular communications will turn digital, leap up the spectrum and even move into video. Shannon's laws show that this will impel vast increases in the cost-effectiveness of communications.

In general, the new rule of radio is the shorter the transmission path, the better the system. Like transistors on semiconductor chips, transmitters are more efficient the more closely they are packed together. As Peter Huber writes in his masterly new book, *The Geodesic Network 2*, the new regime favors "geodesic networks," with radios intimately linked in tiny microcells. As in the law of the microcosm, the less the space, the more the room.

This rule turns the conventional wisdom of microwaves upside down. For example, it is true that microwaves don't travel far in the atmosphere. You don't want to use them to transmit 50,000 watts of Rush Limbaugh over 10 midwestern states, but to accommodate 200 million two-way communicators will require small cells; you don't want the waves to travel far. It is true that microwaves will not penetrate most buildings and other obstacles, but with lots of small cells, you don't want the waves to penetrate walls to adjacent offices.

Microwaves require high-power systems to transmit, but only if you want to send them long distances. Wattage at the receiver drops off in proportion to the fourth power of the distance from the transmitter. Reducing cell sizes as you move up the spectrum lowers power needs far more than higher frequencies increase them. Just as important, mobile systems must be small and light. The higher the frequency, the smaller the antenna and the lighter the system can be.

All this high-frequency gear once was prohibitively expensive. Any functions over two gigahertz require gallium arsenide chips, which are complex and costly. Yet the cost of gallium arsenide devices is dropping every day as their market expands. Meanwhile, laboratory teams are now tweaking microwaves out of silicon. In the world of electronics—where prices drop by a third with every doubling of accumulated sales—any ubiquitous product will soon be cheap.

The law of the telecosm dictates that the higher the frequency, the shorter the wavelength, the wider the bandwidth, the smaller the antenna, the slimmer the cell and ultimately, the cheaper and better the communication. The working of this law will render obsolete the entire idea of scarce spectrum and launch an era of advances in telecommunications comparable to the recent gains in computing. Transforming the computer and phone industries, the converging spirits of Maxwell, Shannon and Shockley even pose a serious challenge to the current revolutionaries in cellular telephony.

Digital signal processors are increasing their cost-effectiveness tenfold every two years. As Donald Steinbrecher says, "That changes wireless from a radio business to a computer business."

THE NEW PC REVOLUTION: PCN

Many observers herald the huge coming impact of wireless on the computer industry, and they are right. But this impact will be dwarfed by the impact of computers on wireless.

In personal communications networks (PCN), the cellular industry today is about to experience its own personal computer revolution. Just as the personal computer led to systems thousands of times more efficient in MIPS per dollar than the mainframes and minicomputers that preceded it, PCNs will bring an exponential plunge of costs. These networks will be based on microcells often measured in hundreds of meters rather than in tens of miles and will interlink smart digital appliances, draining power in milliwatts rather than dumb phones using watts. When the convulsion ends later this decade, this new digital cellular phone will stand as the world's most pervasive PC. As mobile as a watch and as personal as a wallet, these PICOs will recognize speech, navigate streets, take notes, keep schedules, collect mail, manage money, open the door and start the car, among other computer functions we cannot imagine today.

Like the computer establishment before it, current cellular providers often seem unprepared for this next computer revolution. They still live in a world of long and strong—high-powered systems at relatively low frequencies and with short-lived batteries—rather than in a PCN world of low-power systems at microwave frequencies and with batteries that last for days.

Ready or not, though, the revolution will happen anyway, and it will transform the landscape over the next five years. We can guess the pattern by considering the precedents. In computers, the revolution took 10 years. It began in 1977 when large centralized systems with attached dumb terminals commanded nearly 100 percent of the world's computer power and ended in 1987 with such large systems commanding less than one percent of the world's computer power. The pace of progress in digital electronics has accelerated sharply since the early 1980s. Remember yesterday, when digital signal processing (DSP)—the use of specialized computers to convert, compress, shape and shuffle digital signals in real time—constituted an exorbitant million-dollar obstacle to all-digital communications? Many current attitudes toward wireless stem from that time, which was some five years ago. Today, digital signal processors are the fastest-moving technology in all computing. Made on single chips or multichip modules, DSPs are increasing their cost-effectiveness tenfold every two years. As radio pioneer Donald Steinbrecher says, "That changes wireless from a radio business to a computer business."

Thus, we can expect the cellular telephone establishment to reach a crisis more quickly than the mainframe establishment did. The existing cellular infrastructure will persist for vehicular use.

As the intelligence in networks migrates to microcells, the networks themselves must become dumb. A complex network, loaded up with millions of lines of software code, cannot keep up with the efflorescent diversity and creativity among ever more intelligent digital devices on its periphery. This rule is true for the broadband wire links of fiber optics, as intelligent switching systems give way to passive all-optical networks. It is also true of cellular systems.

Nick Kauser, McCaw Cellular Communications' executive vice-president and chief of technology, faced this problem early in 1991 when the company decided to create a North American Cellular Network for transparent roaming throughout the regions of Cellular One. "The manufacturers always want to sell switches that do more and more. But complex switches take so long to program that you end up doing less and less," says Wayne Perry, McCaw vice-chairman. Each time Kauser tried to change software code in one of McCaw's Ericsson switches, it might have taken six months. Each time he wanted to add customer names above a 64,000 limit, Ericsson tried to persuade him to buy a new switch. The Ericsson switches, commented one McCaw engineer, offer a huge engine but a tiny gas tank. The problem is not peculiar to Ericsson, however; it is basic to the very idea of complex switch-based services on any supplier's equipment.

When McCaw voiced frustration, one of the regional Bell operating companies offered to take over the entire problem at a cost of some $200 million. Instead, Kauser created a Signaling System 7 (SS-7) network plus an intelligent database on four Tandem fault-tolerant computers, for some $15 million. Kauser maintains that the current services offered by North American Cellular could not be duplicated for 10 times that amount, if at all, in a switch-based system. Creating a dumb network and off-loading the intelligence on computer servers saved McCaw hundreds of millions of dollars.

The law of the microcosm is a centrifuge, inexorably pushing intelligence to the edges of networks. Telecom equipment suppliers can no more trap it in the central switch than IBM could monopolize it in mainframes.

Kauser should recognize that this rule applies to McCaw no less than to Ericsson. His large standardized systems with 30-mile cells and relatively dumb, high-powered phones resemble big proprietary mainframe networks. In the computer industry, these standardized architectures gave way to a mad proliferation of diverse personal computer nets restricted to small areas and interlinked by hubs and routers. The same pattern will develop in cellular.

COULD 'CHARLES' UPEND MCCAW?

Together with GTE and the regional Bell operating company cellular divisions, McCaw is now in the position of DEC in 1977. With its new ally, AT&T, McCaw is brilliantly attacking the mainframe establishment of the wire-line phone companies. But the mainframe establishment of wires is not McCaw's real competition. Not stopping at central switches, the law of the microcosm is about to subvert the foundations of conventional cellular technology as well. Unless McCaw and the other cellular providers come to terms with the new PC networks that go by the name of PCNs, they will soon suffer the fate of the minicomputer firms of the last decade. McCaw could well be upended by its founder's original vision of his company—a PICO he called "Charles."

Just as in the computer industry in the late 1970s, the fight for the future is already under way. Complicating the conflict is the influence of European and Japanese forces protecting the past in the name of progress. Under pressure from EEC industrial politicians working with the guidance of engineers from Ericsson, the Europeans have adopted a new digital cellular system called Groupe Speciale Mobile (GSM) after the commission that conceived it. GSM is a very conservative digital system that multiplies the number of users in each cellular channel by a factor of three.

GSM uses an access method called time-division multiple access (TDMA). Suggestive of the time-sharing methods used by minicomputers and mainframes to accommodate large numbers of users on centralized computers, TDMA stems from the time-division multiplexing employed by phone companies around the world to put more than one phone call on each digital line. Thus, both the telephone and the computer establishments are comfortable with time division.

Under pressure from European firms eager to sell equipment in America, the U.S. Telephone Industry Association two years ago adopted a TDMA standard similar to the European GSM. Rather than creating a wholly new system exploiting the distributed powers of the computer revolution, the TIA favored a TDMA overlay on the existing analog infrastructure. Under the influence of Ericsson, McCaw and some of the RBOCs took the TDMA bait.

Thus, it was in the name of competitiveness and technological progress, and of keeping up with the Europeans and Japanese, that the U.S. moved to embrace an obsolescent cellular system. It made no difference that the Europeans and Japanese were technologically well in our wake. Just as in the earlier case of analog HDTV, however, the entrepreneurial creativity of the U.S. digital electronics industry is launching an array of compelling alternatives just in time.

Infusing cellular telephony with the full powers of wide and weak—combining Shannon's vision with computer advances—are two groups of engineers from MIT who spun out to launch new companies. Qualcomm Inc. of San Diego is led by former professor Irwin Jacobs and telecom pioneer Andrew Viterbi. A Shannon disciple whose eponymous algorithm is widely used in digital wire-line telephony, Viterbi now is leading an effort to transform digital wireless telephony. The other firm, Steinbrecher Corp., of Woburn, Mass., is led by an inventor from the MIT Radio Astronomy Lab named Donald Steinbrecher.

Like Bernie Bossard and Vahak Hovnanian, the leaders of Qualcomm and Steinbrecher received the ultimate accolade for an innovator: They were all told their breakthroughs were impossible. Indeed, the leaders at Qualcomm were still contending that Steinbrecher's system would not work just weeks ago when PacTel pushed the two firms together. Now they provide the foundations for a radical new regime in distributed wireless computer telephony.

SIGNALS IN PSEUDONOISE

Ten years ago at Linkabit, the current leaders of Qualcomm conceived and patented the TDMA technology adopted as the U.S. standard by the Telephone Industry Association. Like analog HDTV, it was a powerful advance for its time. But